Method For Constructing A Catadioptric Lens System

This application also claims the benefit of U.S. Provisional Application No. 60/459,493, filed April 1, 2003.

Technical Field

This invention relates to a method for making catadioptric lens systems for such applications as interferometric confocal microscopy.

Background of the Invention

A number of different applications of catadioptric imaging systems for far-field and near-field interferometric confocal microscopy have been described such as in U.S. Patent Applications No. 10/028,508, filed December 20, 2001 [ZI-38], and No. 10/366,651, filed February 3, 2003 [ZI-43] entitled "Catoptric And Catadioptric Imaging Systems;" U.S. Provisional Patent Application No. 60/447,254, filed February 13, 2003 and U.S. Patent Application No. 10/778,371, filed February 13, 2004 [ZI-40] both entitled "Transverse Differential Interferometric Confocal Microscopy," U.S. Provisional Patent Application No. 60/448,360, filed February 19, 2003 and U.S. Patent Application No. 10/782,057, filed February 19, 2004 [ZI-41] both entitled "Longitudinal Differential Interferometric Confocal Microscopy for Surface Profiling;" U.S. Provisional Patent Application No. 60/448,250 and U.S. Patent Application No. 10/782,058, filed February 19, 2004 [ZI-42] both entitled "Method and Apparatus for Dark Field Interferometric Confocal Microscopy;" U.S. Provisional Patent Application No.60/442,982, filed January 28, 2003 and U.S. Patent Application No. 10/765,229, filed January 27, 2004 [ZI-45] both entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter;" and U.S. Provisional Application No. 60/459,425, filed April 1, 2003 and U.S. Patent Application No.___, filed April 1, 2004 [ZI-50] both entitled "Joint Measurement Of Fields Of Orthogonally Polarized Beams Scattered/Reflected By An Object In Interferometry." The above-mentioned

patent applications and provisional patent applications are all by Henry A. Hill and the contents are incorporated herein by reference in their entirety.

In each of the applications of catadioptric imaging systems for each of the cited U.S. Patent Applications and U.S. Patent Provisional Patent Applications, tight tolerances are placed on the manufacture of optical elements. In addition to the tolerances normally encountered in designing a diffraction limited imaging system, there are tolerances imposed by the interferometric confocal microscopy applications. The additional tolerances are for example on radii of curvature of certain lens elements with respect to radii of curvature of certain other lens elements and on relative locations of centers of curvature of lens elements.

The additional tolerances lead to improved performance of a catadioptric imaging system, *e.g.*, with respect to increasing the average intensity of desired images by a factor of approximately 2 or more and reduced intensity of spurious beams by one or more orders of magnitude, and in addition make it possible to realize interferometric reduction of background fields. The interferometric reduction of background fields leads to a reduction of statistical errors. The increase in intensity of desired images and the reduction of statistical errors lead to an increase in signal-to-noise ratios and to a concomitant increase in through put of a metrology tool using the catadioptric imaging system. The interferometric reduction of background fields further leads to a reduction systematic errors. A consequence of the reduction of systematic errors is a reduction of the computational task required to invert arrays of interference signal values to a multi-dimensional image of an object.

Summary of the Invention

In general, in one aspect the invention features a method of fabricating a catadioptric lens system. The method involves: fabricating a single catadioptric lens element having a bottom surface and an upper surface, the upper surface having a convex portion and a concave portion, both the convex and concave portions sharing a common axis of symmetry; cutting apart the catadioptric lens element to form 2n pie-shaped segments, wherein n is an integer; and reassembling the 2n pie-shaped

segments to form the catadioptric lens system with n of the 2n pie-shaped segments being located above a common plane and the rest of the 2n pie-shaped elements being below the common plane.

Other embodiments include one or more of the following features. Cutting the catadioptric lens element to form the 2n pie-shaped segments is accomplished by cutting along a set of planes each of which contains the common axis. The 2n pie-shaped segments are identically shaped. The parameter n = 1 or 2. Each of the four pie-shaped segments is a 90° segment of the single catadioptric lens element. Reassembling involves arranging each of the n pie-shaped segments that are above the common plane to be opposite to and aligned with a corresponding different one of the n pie-shaped segments that are below the common plane. The convex portion is a reflective portion of the catadioptric lens element and the concave portion is a refractive portion of the catadioptric lens element. Reassembling the four pie shaped segments relative to a common plane involves placing two of the four segments are above the plane with their bottom surfaces being substantially parallel to and facing the common plane and placing the other two of the four segments are below the common plane with their bottom surfaces substantially parallel to and facing the common plane. Reassembling also involves orienting the four segments so that each one of the two segments above the common plane are aligned with and adjacent to a corresponding one of the two segments that are below the common plane. Reassembling further involves orienting the two segments that are above the common plane so that they share an axis of symmetry and are radially opposite each other relative to that shared axis of symmetry.

In general, in another aspect, the invention features another method of fabricating a catadioptric lens system. The method involves: fabricating a single catadioptric lens element having a bottom surface and an upper surface, the upper surface having a convex portion and a concave portion, both the convex and concave portions sharing a common axis of symmetry; cutting apart the catadioptric lens element to form two identically pie-shaped segments; and reassembling the two pie-shaped segments to form at least part of the catadioptric lens system with one of the two pie-shaped segments being located above a common plane and the other of

the two pie-shaped elements being below the common plane, wherein the bottom surfaces of the two pie-shaped elements are facing each other and substantially parallel to the common plane, and wherein the two pie-shaped segments are aligned with each other.

In general, in still another aspect, the invention features another method of fabricating a catadioptric lens system. The method involves: fabricating a single catadioptric lens element having a bottom surface and an upper surface, the upper surface having a convex portion and a concave portion, both the convex and concave portions sharing a common axis of rotational symmetry; cutting apart the catadioptric lens element to form four substantially identical segments, wherein cutting involves cutting the catadioptric element along at least one plane that contains the common axis; and reassembling the four segments to form the catadioptric lens system with two of the four segments being located above a common plane and the other two of the four elements being below the common plane, wherein the reassembled four segments have their bottom surfaces substantially parallel to the common plane, and wherein each of the two segments that is above the plane is aligned with and adjacent to a corresponding different one of the two segments that are below the common plane.

An advantage of one or more embodiments is a reduction of cost in the manufacture of lens elements for a catadioptric imaging system in interferometric confocal microscopy.

Another advantage of one or more embodiments is the improvement of performance of a catadioptric imaging system in interferometric confocal microscopy.

Another advantage of one or more embodiments is the increase of the average intensity of desired images by a factor of approximately 2 or more.

Another advantage of one or more embodiments is a reduction of intensity of spurious beams by one or more order of magnitudes,

Another advantage of one or more embodiments is that it makes it possible to realize interferometric reduction of background fields.

Another advantage of one or more embodiments is an increase in signal-to-noise ratios and to a concomitant increase in through put of a metrology tool using a catadioptric imaging system.

Another advantage of one or more embodiments is a reduction systematic errors as a consequence of the interferometric reduction of background fields.

Another advantage of one or more embodiments is the reduction of the computational task required to invert arrays of interference signal values to a multi-dimensional image of an object wherein the arrays of interference signal values are obtained with an interferometric confocal microscopy system that uses a catadioptric imaging system.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

Brief Description of the Drawings

Fig. 1 is a schematic drawing of a catoptric imaging system including a reflective surface and a beam splitter.

Fig. 2 is a schematic drawing of another catoptric imaging system including a reflective surface and a beam splitter.

Fig. 3 is a schematic drawing of a catadioptric imaging system including a reflective surface, a beam splitter, and two refractive surfaces.

Fig. 4 is a schematic drawing of a catoptric imaging system including two reflecting surfaces constructed and positioned such that interferometric effects lead to increased light intensity at the image point.

Fig. 5 is a schematic drawing of a catadioptric imaging system similar to the imaging system in Fig. 4 including refractive surfaces that reduce optical aberrations.

Fig. 6 is a schematic drawing of another catadioptric imaging system similar to the imaging system in Fig. 5 that generates two image points that are spatially separated in the transverse direction to the optical axis.

Fig. 7 is a schematic drawing of another catadioptric imaging system similar to the imaging system in Fig. 5 that generates two image points that are spatially separated in the longitudinal direction relative to the optical axis.

Fig. 8 is a schematic drawing of a catadioptric imaging system similar to the imaging system in Fig. 4 but including refractive surfaces that are Fresnel mirrors.

Fig. 9 is a perspective drawing of a catadioptric imaging system.

Fig. 10 is a perspective drawing of a catadioptric imaging system with the elements separated for purposes of illustration.

Detailed Description

Referring to Fig. **1**, a catoptric imaging system **100** includes an object point **160**, an image point **162**, a beam splitter **150**, a curved reflective surface **132**, and light transmitting elements **130** and **140**. Light emanating from the object point **160** passes through the light transmitting element **130** and is incident on the beam splitter **150**. The beam splitter **150** reflects and transmits portions of the incident light beams. In the presently described embodiment, the portion of light that is initially transmitted is ignored and it is omitted from Fig. **1**. The reflected portion is shown in Fig. **1** and is incident onto the reflective surface **132**. The surface **132** is constructed such that each light ray emanating from the object point **160** that is reflected from the beam splitter **150** and incident onto the surface **132** is reflected to the image point **162** after being transmitted by the beam splitter **150**. In other words, light emanating from the object point **160** is focused onto the image point **162** by the following path: i) light is emanated from the object point **160**; ii) reflected by beam splitter **150**; iii) reflected by reflective surface **132**; iv) transmitted by the beam splitter **150**; and v) converges onto the image point **162**.

Because reflecting surface **132** causes the focusing of the rays to the image point, and not refraction by media **130** and **140**, the image plane is independent of the spectral region used in image formation (provided that media **130** and **140** do not substantially differ in index). In other words, there is no longitudinal chromatic aberration. Accordingly, a large spectral range can be used for image formation.

The index of refraction of medium **130** impacts the numerical aperture of the system. In particular, the numerical aperture of system **100** scales linearly with the index of refraction of the medium **130**. Although by no means limiting, the rest of this discussion assumes that the indices of refraction for elements **130** and **140** (and their analogs in other embodiments) are substantially the same.

In one embodiment, the features of system **100** are achieved with the following design. Given the object point **160** and the image point **162**, beam splitter **150** is positioned to lie in the plane defined by points that are equidistant from the object and image points. Furthermore, reflective surface **132** is designed to be concentric with the image point **162**. As a result of this construction, a light ray emanating from the object point at an angle ϕ is incident on the beam splitter at some point P with an angle of incidence of ϕ. By design light is incident onto surface **132** at a normal angle of incidence and therefore such light rays are reflected through **180** degrees. Furthermore, after reflection from surface **132**, the light is incident on the beam splitter at the same point P with angle of incidence of ϕ and after transmission by the beam splitter **150** the light ray is incident on the image point with angle of incidence of ϕ.

As described above, the light incident on the image point is both reflected and transmitted by the beam splitter surface. Therefore, the light reaching image point **162** is proportional to $R(\phi)T(\phi)$, where R and T are the reflection and transmission coefficients of beam splitter **150**, respectively. Both of these coefficients are typically dependent on the angle of incidence. Using techniques known in the art, beam splitter **150** is designed such that for some angle ϕ' beam splitter **150** is ideal. That is, for some angle ϕ', $R(\phi') \cong T(\phi') \cong 0.5$. As the angle of incidence differs from ϕ', the coefficients will often demonstrate non-ideal beam splitter behavior. Specifically, the behavior deviates from the ideal by some $\delta(\phi)$, and $R(\phi) = 0.5 + \delta(\phi - \phi')$ and $T(\phi) = 1 - R(\phi) = 0.5 - \delta(\phi - \phi')$ where $\delta(0) = 0$. Because the light rays incident on image point **162** as shown in Fig. 1 are both reflected and transmitted, then $T(\phi)R(\phi) = 0.25 - \delta(\phi - \phi')^2$. Thus even though the

beam splitter may deviate from an ideal beam splitter with some deviation $\delta(\phi)$, the non-ideal behavior will only impact the light intensity to second order in $\delta(\phi)$.

Furthermore, this embodiment has an object point image that is diffraction limited. Although other points in the object plane may not be diffraction limited, there does exist a planar disc centered on the object point and parallel with the beam splitter **150** whose image is also a flat disc of the same radius. In other words, the image plane is flat and the magnification is 1.

Element **130** and surface **132** may be made in a number of ways. Transmitting element **130** and the reflecting surface **132** may be made from a solid light-transmitting medium (*e.g.* fused silica). In this case, the solid light-transmitting medium can be shaped to have one side that is to match the shape of the beam splitter **150** and another side whose shape matches the desired shape for reflecting surface **132**. By suitably depositing a reflecting film onto the curved surface, the reflecting surface **132** is formed. This could be accomplished using any of the well-known techniques in the art for forming reflecting films. The reflecting film is not applied within some neighborhood of the object point **160** (not shown). Instead the surface near the object point would be constructed to allow light rays to enter into the imaging system. For example, an antireflection coating may be applied to surface **132** in the vicinity of object point **160**. Such an aperture allows light rays from the object point to enter into the imaging system.

In another embodiment, light-transmitting element **130** may be a hollow region of vacuum or filled with a light transmitting gas or fluid. In such embodiments, the reflective surface **132** may be formed onto some mechanically supporting substrate (not shown) and its external surface is either intrinsically reflective (*e.g.* a polished metal surface) or is made reflective by application of a reflective film. Furthermore, an aperture is formed in the vicinity of the object point **160** such that light can enter the imaging system (not shown).

In other embodiments, the reflecting surface **132** may be a non-smooth and/or discontinuous surface. For example, the reflecting surface may be formed by an array of flat reflecting surfaces positioned to be substantially concentric with the image point **162** so as to provide the same optical function as the surface **132** in Fig.

1. Furthermore reflecting surface **132** may have deviations from a concentric shape (*e.g.* elliptical or parabolic). Such deviations may be useful in correcting for higher order aberrations.

In some embodiments of system **100**, element **130** is a high-index material and element **130** and beam splitter **150** are positioned such that element **130** contacts object point **160** to thereby maximize the numerical aperture of the imaging system. This is a non-limiting case, however, and in other embodiments the object point need not contact element **130**. Similarly, element **140** need not contact image point **160**. Moreover, in subsequently described embodiments, the object point and/or the image point need not contact an element of the imaging system, although, depending on the embodiment, this may be preferable to maximize numerical aperture.

Although not intended to be limiting in any way, as a theoretical curiosity it is noteworthy to point out that imaging system **100** functions equivalently to a pair of planar elements each having opposite indices of refraction (*i.e.*, one element having a positive index $+n$, and the other element having a negative index $--n$). In particular, refraction at the interface between two such elements causes light rays emitted from the object point to bend and focus to the image point. This can be seen from a trivial application of Snell's law of refraction. Such bending and focusing is effectively achieved in system **100** by the initial reflection from beam splitter **150** and the subsequent reflection by reflecting surface **132**. A similar effect is also present in the subsequently described embodiments.

From the design of imaging system **100**, it is clear that light that initially is transmitted by the beam splitter is ignored and only the reflected component is used. Other imaging systems can be designed such that the initially transmitted component is utilized and the reflected component is discarded. Referring to Fig. **2**, a catoptric imaging system **200** includes an object point **260**, an image point **262**, a beam splitter **250**, a curved reflective surface **242**, and light transmitting media **230** and **240**. The embodiment of Fig. **2** is similar to that of Fig. **1** except that in the embodiment of Fig. **2**, reflecting surface **242** is positioned to receive light transmitted by the beam splitter surface, whereas the reflecting surface in Fig. **1** is positioned to receive light reflected by the beam splitter surface. In an embodiment

of system **200**, the reflecting surface **242** is concentric with object point **160**. As is the case with the embodiment in Fig. **1**, the intensity of incident light imaged to image point **262** is proportional to $T(\phi)R(\phi) = 0.25 - \delta(\phi - \phi')^2$. Thus the image point light intensity has no first order deviations due to non-ideal beam splitter behavior. Furthermore, as described with reference to Fig. **1** a transparent window or an apertures in surface **242** allows access to the image point **262** for light emanating from object point **132**.

In the embodiments of Figs. **1** and **2**, although the object point is diffraction limited, the points in the vicinity of the object point may not be. Such points may suffer from certain optical aberrations. Such aberrations may be corrected for a large part of the object plane by introducing refractive surfaces.

Referring to Fig. **3**, a catadioptric imaging system **300** includes an object point **360**, an image point **362**, a beam splitter **350**, a curved reflective surface **332**, a plano-concave-convex element **330**, a plano-concave element **340**, and plano-convex elements **320** and **380**. The common center of curvature for surface **322** of element **320** is the object point **360**. The common center of curvature for surface **344**, surface **332** of element **330**, and surface **382** of element **380** is image point **362**. Element **320** and element **330** are formed such that the radius of curvature of surface **322** of element **320** is substantially the same as the radius of curvature of surface **334** of element **330**. Element **340** and element **380** are formed such that the radius of curvature of surface **344** of element **340** is substantially the same as the radius of curvature of surface **382** of element **380**. Surfaces **322** and **344** are preferably coated with an antireflection coating.

The refracting surfaces in system **300** provide additional degrees of freedom that can be used to reduce optical aberrations in the image field. In particular, any of the index of refraction of elements **320, 380, 340** and the radius of curvature of surface elements **334, 344, 332** may be varied to reduce such aberrations. For example, optical ray tracing methods may be used to calculate the amplitude of the various aberrations as functions of such variables and in this way particular values of the parameters can be found that minimize the aberrations. Such optimizations may also take into account other design criteria such as magnification, planarity of the

image field, numerical aperture, optical absorption and other material limitations. Notably, for example, the numerical aperture of system **300** scales with the index of refraction of the element **320**. Thus, by use of a high index material, the numerical aperture can be improved. Moreover, an optimization may fix the indices of refraction for elements **320**, **330**, **340**, and **380** simply because specific materials are to be used for these elements.

In some embodiments, element **380** or element **320** may be excluded. Elements **380** or **320** may be replaced by a void to be filled with a gas, liquid or vacuum. In some embodiments only one refractive surface may be used. In such cases, the index of refraction of element **380** or **320** matches the index of elements **330** and **340** such that interface **322/334** or **344/382** is no longer a refractive surface. Use of a void provides access to the image point or object point. Such access may be useful, for example, to position a detector near the image point.

As described above, the light intensity at the image point for imaging system **100**, **200**, and **300** are proportional to $T(\phi)R(\phi) = 0.25 - \delta^2$. Even in the ideal case, where $\delta = 0$, only 25% of the available light reaches the image point.

Referring to Fig. **4**, a catoptric imaging system **400** includes an object point **460**, an image point **462**, a beam splitter **450**, a curved reflective surface **432**, a curved reflective surface **442** and plano-convex elements **430** and **440**. The reflective surface **442** is constructed such that light rays emanating from the object point **460** are focused to the image point **462** by following the path: i) the light emanates from the object point; ii) is transmitted by the beam splitter **450**; iii) is reflected by surface **432**; iv) is reflected by the beam splitter **450**; v) is incident onto the image point **462**. This can be accomplished by designing curved surface **442** to be concentric with the object point **460**. Similarly the reflective surface **432** is constructed such that light rays emanating from the object point are focused to image point **462** by following the path: i) the light emanates from the object point; ii) is reflected by the beam splitter **450**; iii) is reflected by surface **432**; iv) is transmitted by beam splitter **450**; and v) is incident onto the image point **462**. This can be accomplished by designing curved surface **432** to be concentric with the image point **462**.

In the embodiment described for Fig. **4**, both the initially reflected and initially transmitted beams from the beam splitter are used. A beam is split by beam splitter **450** into two portions that are then reflected by surfaces **432** and **442**, respectively, back to the same point on the beam splitter. Generally, the two portions recombine interferometrically to produce two new beams. One beam is directed to the image point **462** and the other is directed to the object point **460**. The intensities of the respective beams depend on the difference in optical path length for the beam portions reflected from surfaces **432** and **442**. Fig. **4** labels the two optical paths for the portions as OPL1 and OPL2. The optical path lengths for the portions corresponding to each ray are matched such that the two beams interfere constructively to direct all of the optical energy to the image point. Thus, the concentric curved surfaces **442** and **432** are positioned and shaped to agree to within a small fraction of a wavelength. Nonetheless, even where the optical path lengths are not exactly matched for all rays, the transmission to the image point can be enhanced relative to the earlier embodiments where transmission is limited to 25%.

The matched concentric curved surfaces **442** and **432** may be constructed using known techniques for fabricating precision surfaces. For example, a master set of reflecting surfaces **432** and **442** are constructed using high precision techniques for grinding spherical surfaces in conjunction with high precision metrology techniques. From the master set, replication techniques are employed to mass-produce copies of the surfaces. Such methods are commonly used to produce diffraction gratings. Furthermore, if there is some uncertainty in the resulting structures, testing can be used to retain only those copies that enhance transmission. Such testing may include the light transmission properties and surface profile measurements.

Similar to the discussion of imaging system **300**, the object point of imaging system **400** is diffraction limited, but points in the vicinity of the object point may be distorted by aberrations. By the use of refractive surfaces it is possible to make these aberrations substantially zero for points in the object plane displaced from the object point. Referring to Fig. **5**, an catadioptric imaging system **500** includes an

object point **560**, an image point **562**, a beam splitter **550**, a curved reflective surface **532** and **542**, plano-concave-convex light transmitting elements **530** and **540**, and plano-convex elements **520** and **580**. Element **520** and element **530** are formed such that the radius of curvature of surface **522** of element **520** is substantially the same as the radius of curvature of surface **534** of element **530**. Element **540** and element **580** are formed such that the radius of curvature of surface **544** of element **540** is substantially the same as the radius of curvature of surface **582** of element **580**. In the described embodiment, the common center of curvature for surface **522** of element **520**, for surface **534** of element **530**, and for surface **542** of element **540** is the object point **560**. Furthermore in the described embodiment the common center of curvature for surface **544** of element **540**, for surface **532** of element **530**, and for surface **582** of element **580** is the image point **562**. Surfaces **522** and **544** are preferably coated with an antireflection coating. Furthermore, similar to the imaging system **400** of Fig. **4**, the surfaces **542** and **532** are constructed such that light rays which are split by the beam splitter **550** recombine at a common point on beam splitter **550** and interfere constructively to enhance the light transmission to the image point **562**.

In some embodiments, element **580** is composed of air. This allows for optical detection devices like CCD's to be positioned easily near the image point. The radii of curvature r_{522}, r_{534}, and r_{544} of the refractive surfaces **522, 534**, and **544**, respectively, are chosen to minimize certain optical aberrations. Non-limiting examples of radii of curvature are shown in Table 1 for several different combinations of refractive materials with $r_{532} = r_{542} = 50\,\mathrm{mm}$ where r_{532} and r_{542} are the radii of curvature of surfaces **532** and **542**, respectively. It is assumed that element **580** is air. Results of geometrical ray traces through systems employing the combination of refractive materials listed in Table 1 show that the images formed by the first embodiment are diffraction limited for an object field of 0.5 mm with an object space numerical aperture equal to 0.77 times the index of refraction of element **520** where n_{520}, n_{530}, and n_{540} are the refractive indices of elements 520, 530, and 540, respectively.

In additional embodiments, the reflective surfaces in, for example, the embodiments of any of Figs. **4** or **5**, may be reconfigured to produce an imaging system that images the object point to two spatially separated image points. The two image points may be displaced relative to each other along the optical axis, in a plane orthogonal to the optical axis, or a combination of both. Such embodiments may also be used in "reverse" to image two spatially separated object points to a common image point. The reconfiguration of the reflective surfaces may include, for example, adjusting their relative positions and/or changing their radius of curvature.

Referring to Fig. **6**, a catadioptric imaging system **1000** is shown that is similar to system **400** of Fig. **5**. System **1000** includes an object point **1060**, spatially separated image points **1062** and **1064**, a beam splitter **1050**, curved reflective

Table 1

Lens 520	Element 530,540	n_{520} (633nm)	n_{530}, n_{540} (633nm)	r_{522}, r_{534} (mm)	r_{544} (mm)
GaP[a]	Fused Silica	3.3079	1.4570	8.467	17.500
BSO[b]	Fused Silica	2.5500	1.4570	5.551	12.270
YSZ[c]	Fused Silica	2.1517	1.4570	3.000	6.720
YAG[d]	Fused Silica	1.8328	1.4570	2.997	16.030

[a] GaP: Gallium phosphide

[b] BSO: Bismuth silicon oxide, $Bi_{12}SiO_{20}$

[c] YSZ: Ytterbium stabilized zirconia, ZrO_2:12%Y_2O_3

[d] YAG: Yttrium aluminum garnet, $Y_3Al_5O_{12}$

surfaces **1032** and **1042**, plano-convex-concave light transmitting elements **1030** and **1040**, and plano-convex elements **1020** and **1080**. Element **1020** and element **1030** are formed such that the radius of curvature of surface **1022** of element **1020** is substantially the same as the radius of curvature of surface **1034** of element **1030**. Beam splitter **1050** is oriented normal to an optical axis **1002** connecting object

point **1060** to image point **1062**. As in the embodiment of Fig. **5**, the center of curvature of reflective surface **1042** coincides with object point **1060**. Thus, a first set of rays **1092** corresponding to those rays from object point **1060** transmitted by beam splitter **1050** reflect from curved surface **1042** and then reflect from beam splitter **1050** to focus onto image point **1062**.

However, in contrast to the embodiment of Fig. **5**, the center of curvature **1063** of reflective surface **1032** is displaced from image point **1062** by an amount δy_1 along a direction normal to optical axis **1002**, which corresponds to reflective surface **1032** being displaced by the amount δy_1 along the direction normal to optical axis **1002**. As a result, a second set of rays **1094** corresponding to those rays from object point **1060** reflected by beam splitter **1050** reflect from curved surface **1032** and then transmit through beam splitter **1050** to focus onto image point **1064**, which is displaced from center of curvature 1063 by an amount $\delta y_2 = \delta y_1$ along the direction normal to optical axis **1002**. Thus, in system **1000** image points 1062 and **1064** are displaced from one another by an amount $2\delta y_1$ along the direction normal to optical axis **1002**.

Additional elements **1020** and **1080** provide refracting surfaces selected minimize aberrations as described above. For simplicity, the effects of any such refraction are not shown in Fig. **6** with respect to the path of rays **1092** and **1094**.

In another similar embodiment shown in Fig. **7**, the center of curvature of one of the reflective surfaces is displaced along the optical axis.

Referring to Fig. **7**, a catadioptric imaging system **1100** includes an object point **1160**, spatially separated image points **1162** and **1164**, a beam splitter **1150**, curved reflective surfaces **1132** and **1142**, plano-convex-concave light transmitting elements **1130** and **1140**, and plano-convex elements **1120** and **1180**. Element **1120** and element **1130** are formed such that the radius of curvature of surface **1122** of element **1120** is substantially the same as the radius of curvature of surface **1134** of element **1130**. Beam splitter **1150** is oriented normal to an optical axis **1102** connecting object point **1160** to image point **1162**. As in the embodiment of Fig. **4**, the center of curvature of reflective surface **1142** coincides with object point **1160**. Thus, a first set of rays **1192** corresponding to those rays from object point **1160**

transmitted by beam splitter **1150** reflect from curved surface **1142** and then reflect from beam splitter **1150** to focus onto image point **1162**.

However, in contrast to the embodiment of Fig. **5**, the center of curvature **1163** of reflective surface **1132** is displaced from image point **1162** by an amount δz_1 along optical axis **1102**, which corresponds to reflective surface **1132** being displaced by the amount δz_1 along optical axis **1102**. As a result, a second set of rays **1194** corresponding to those rays from object point **1160** reflected by beam splitter **1150** reflect from curved surface **1132** and then transmit through beam splitter **1150** to focus onto image point **1164**, which is displaced from center of curvature **1163** by an amount δz_2 along optical axis **1102**. The amounts δz_1 and δz_2 are related to one another by the spherical lens formula $1/s_1 + 1/s_2 = 2/R$, where R is the radius of curvature of reflective surface **1132**, $s_1 = R - \delta z_1$, and $s_2 = R + \delta z_2$. Thus, in system **1100** image points **1162** and **1164** are displaced from one another by an amount $\delta z_1 + \delta z_2$ along optical axis **1102**.

Additional elements **1120** and **1180** provide refracting surfaces selected minimize aberrations as described above. For simplicity, the effects of any such refraction are not shown in Fig. **7** with respect to the path of rays **1192** and **1194**.

In further embodiments, the reflective surface may be displaced both by an amount δy_1 along a direction normal to the optical axis and by an amount δz_1 along optical axis **1102**. In such embodiments, the longitudinal displacement of the second image point is the same, however, the transverse displacement further includes a magnification factor $M = s_2/s_1$, in which case $\delta y_2 = M\delta y_1$.

In yet further embodiments, the other of the reflective surfaces may be displaced, or both surfaces may be displaced. Furthermore, the radius of curvature of one or both of the reflective surfaces may be modified, which have a similar effect as that of the longitudinal displacement described with reference to Fig. **7**.

In additional embodiments of the catoptric systems described herein, one or both of the reflective surfaces in any of the embodiments described above, may be a Fresnel mirror. As defined above, a Fresnel mirror is a reflecting surface formed by multiple curved facets each having a common center of curvature.

Referring to Fig. **8**, for example, a catadioptric imaging system **1200** includes an object point **1260**, image point **1262**, a beam splitter **1250**, curved reflective surfaces **1232** and **1242**, and plano-convex-concave light transmitting elements **1230** and **1240**. System **1200** is similar to that of Fig. **4**, except both of the reflective surfaces are Fresnel mirrors. In particular, reflective surface **1232** includes curved facets **1232a**, **1232b**, and **1232c**, which each have a common center of curvature at image point **1262**. Facets **1232b** and **1232c** may be fabricated, for example, as an outer annular section of a lens having a surface with the same radius of curvature as facet **1232a**. Similarly, reflective surface **1242** includes curved facets **1242a**, **1242b**, and **1242c**, which each have a common center of curvature at object point 1260. Furthermore, facets **1242b** and **1242c** may be fabricated, for example, as an outer annular section of a lens having a surface with the same radius of curvature as facet **1242a**.

Referring still to Fig. **8**, implementing the Fresnel mirrors allows oblique rays emerging from object point **1260**, such as rays **1261**, to be imaged to image point **1262** in addition to less oblique rays such as rays **1263**. In contrast, oblique rays **1261** would not be imaged to the image point by the system if it only included central facets **1232a** and **1242a** (as indicated by the dashed lines extending facets **1232a** and **1242a**). Thus, implementing the Fresnel mirrors increases the numerical aperture and working distance of the system.

In each of the embodiments, the requirements for matched elements with respect to tolerances on radii of curvature, thickness of plano-convex elements, thickness of a plano-concave-convex element, and lateral shears of elements are typically associated with respect to a pair of elements or a set of four elements that have pie-sections as apertures such as shown in perspective drawing in Fig. **9** for catadioptric imaging system **600**. System **600** comprises elements **630, 632, 640,** and **642** and each of the four elements represents a 45 degree pie-section. Elements **630, 632, 640,** and **642** are constructed by cutting a single element, such as element **530** shown in Fig. **5,** into four sections. In general, that starting element is a catadioptric lens element that includes a planar bottom surface and an upper surface having a convex reflective portion and a concave refractive portion, with both the

convex and concave portions sharing a common axis of symmetry (typically, they are spherical or substantially spherical surfaces). As a consequence of the way they are produced, the elements **630, 632, 640**, and **642** have the same radii of curvature and thickness of the plano-convex-concave dimension to the same accuracy that the surface **532** shown in Fig. 5 can be manufactured, *e.g.*, $\lambda/10$.

Fig. **10** shows the catadioptric system of Fig. **9** with the elements separated in order to display the features more clearly.

The use of matched pie-sections is of particular value in ellipsometric interferometric applications of the catadioptric imaging system such as described in the above-mentioned U.S. Provisional Application entitled "Joint Measurement Of Fields Of Orthogonally Polarized Beams Scattered/Reflected By An Object In Interferometry." The pie-sections may comprise sections with angles less than 45 degrees.

The relative radii of curvature of elements **630, 632, 640**, and **642** may be modified by a fraction λ or of the order of λ with the deposition of a thin layer on the respective concave or convex surfaces. Also the thickness of the plano-convex-concave dimension of elements **630, 632, 640**, and **642** may be modified by a fraction λ or of the order of λ with the deposition of a thin layer on the respective plano surfaces. The addition of the thin layers would serve for example the purpose of introducing a $\pi/2$ or π phase shift in a measurement beam.

In catadioptric imaging system comprising pie-sections such as shown in Fig. **6**, the construction method described herein easily accommodates the introduction of lateral shears of elements **630, 632, 640**, and **642** as desired in an end use application.

The use of matched pie-sections of a catadioptric imaging system also has the additional advantage of permitting two or more different matched pie-sections having different properties, *e.g.*, numerical apertures, different $\pi/2$ or π phase shifts in a measurement beam, and/or different operating wavelengths.

Other embodiments are within the following claims.